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# Estimated Sediment Reduction with Forestry Best Management Practices Implementation on a Legacy Forest Road Network in the Northern Rocky Mountains

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This study modeled changes in sediment delivery to streams in response to systematic Best Management Practice (BMP) upgrades to a 28,000 km forest road network in western Montana and northern Idaho. Key BMPs applied included installing more frequent road drainage features to disperse runoff entering streams, managing public road access to reduce the need for ongoing maintenance, increasing road surface vegetative cover, and installing supplemental filtration near streams. The Washington Road Surface Erosion Model (WARSEM), with locally validated model assumptions, was used to estimate fine sediment delivery before and after BMP upgrades. Results from 10 repeated watersheds (inventoried and modeled before and after BMPs) estimated that sediment delivery (weighted by watershed road length) was reduced by 46% (watershed range: –84% to +57%) over a 10–15-year period. Delivery rates from these watersheds were similar to an additional 22 watersheds that were inventoried after BMP upgrades had been completed. Road sediment delivery from surface erosion estimated by WARSEM in BMP-upgraded watersheds represented less than a 5% increase above background erosion rates in this region.

**Keywords:** legacy forest roads, sediment, surface erosion, Best Management Practices, road runoff, road erosion control

## Introduction

Forest roads that are improperly located, constructed, or maintained can deliver sediment-laden stormflow into streams, with negative effects on water quality and aquatic ecology. Comprehensive reviews of these impacts are provided by Furniss et al. (1991), NCASI (2001), and Endicott (2008). A leading cause of stream impairment nationally is sediment (USEPA 2017), and roads can increase sediment delivery to streams from erosion of road surfaces (Megahan and Kidd 1972, Reid and Dunne 1984, Bilby et al. 1989, Luce and Black 2001), mass erosion generated by landslides, or stream crossing failure (Sidle and Ochiai 2006, Furniss et al. 1991).

Best Management Practices (BMPs) for forest roads have been developed over the past half-century to minimize these impacts (Ice et al. 1997). Road BMPs exist for design, placement, construction practices, maintenance, temporary decommissioning, and complete decommissioning/reclamation (NCASI 2009). Recent literature reviews suggest that implementation of BMPs can reduce the impacts of forest roads on water quality and ecology (Ice and Schilling 2012, Cristan et al. 2016). Examples of modern BMPs include:

- Minimize the road density and area of road prism.
- Locate roads away from streams [i.e., outside Streamside Management Zones (SMZs)] unless stream crossings are required.
- Install road drainage features at regular intervals to reduce erosion and divert overland flow from roads onto undisturbed hillslopes to promote water infiltration.
- Ensure road runoff is disconnected from streams toward filtration areas.
- Re-vegetation and ground cover establishment on disturbed areas near streams (cutslopes, fillslopes, and road ditches).
- Gravel surfacing on highly erodible soils or when wet weather use is required.

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- Install supplemental filtration for suspended sediments where needed to prevent direct sediment delivery to streams. This includes slash windrows, silt fences, straw bales, etc.
- Install appropriately sized stream crossing structures that allow passage of flood flows, sediment, wood, and minimize disruptions to aquatic species movement.
- Manage/restrict seasonal road access to vehicles as needed to prevent rutting, and perform any necessary maintenance (grading) through time.
- Consider road closure or decommissioning of unneeded roads.

To address documented impacts to salmon habitat, states in the Pacific Northwest adopted regulatory BMP programs by the mid-1970s through state-legislated Forest Practices Acts (Ice et al. 2004). The 1987 reauthorization of the federal Clean Water Act further promoted state nonpoint source pollution planning through Section 319. It is up to states to select regulatory, non-regulatory (voluntary), or quasi-regulatory approaches to address nonpoint source pollution (Ice et al. 1997, Cristan et al. 2017). Montana adopted statewide voluntary BMPs in 1989, and a regulatory Streamside Management Zone (SMZ) Act passed the state legislature in 1991 (Montana Code Annotated 75-5-301). Today, all states have adopted BMP programs or forest practices acts for forest management activities, including roads (Cristan et al. 2017).

Nationally, state monitoring of BMP implementation shows high levels of compliance with forestry BMPs, regardless of whether state programs are regulatory or voluntary (Cristan et al. 2017). But recently, the US Environmental Protection Agency (USEPA) has expressed concern about "legacy roads" that were constructed prior to state adoption of BMP programs, and whether or not these roads are being effectively addressed (USEPA 2016). In some cases, older roads were not sited properly, are inadequately drained, and deliver significant quantities of fine sediment to streams (Ice and Schilling 2012). USEPA intends to facilitate information exchange on the impacts of legacy roads and their management (USEPA 2016).

In 2000, Plum Creek Timber Company (PCTC) owned 590,600 ha of forest land in western Montana and 16,300 ha in northern Idaho[1] (Figure 1). This land base was accessed by a 28,000 km forest road network, which included roads on the ownership, as well as jointly managed roads leading to the ownership. It is estimated that 85–90% of this road length was built prior to Montana's adoption of forestry BMPs in 1989 and passage of the Idaho Forest Practices Act in 1974. In steeper terrain, old mainline roads accessing watersheds often were built along watercourses (i.e., stream-adjacent roads), contrary to contemporary forestry BMP standards. In more gently sloping glaciated terrain, watersheds were accessed by fewer stream-adjacent roads. Original culverts on legacy roads in this region often only accommodated a 5–10-year flood event, rather than being designed to meet or exceed the current BMP standard of a 25-year event in Montana and a 50-year event in Idaho. Old roads were constructed with inadequate surface drainage by today's BMP standards. Water would often be routed hundreds to thousands of meters down roads (in roadside ditches or in tire depressions/ruts in the road surface) and deliver directly to streams.

PCTC began upgrading legacy roads by the early 1990s in conjunction with ongoing forest management activities under Montana's voluntary BMP program. In 1994, PCTC enrolled its lands in the Sustainable Forestry Initiative (SFI™), which requires adherence to state BMPs as a condition of certification (SFI 2015). In November 2000, PCTC entered into a 30-year Native Fish Habitat Conservation Plan (NFHCP) agreement with the US Fish and Wildlife Service (USFWS) to protect and restore streams on this ownership (USFWS et al. 2000). Under the plan, PCTC had 10–15 years (depending on watershed priority) to upgrade legacy roads to current BMP standards. All new roads were constructed following BMPs.

This study was undertaken to help address a critical information gap on the effectiveness of state BMP programs at addressing legacy roads. Specific objectives were to: 1) Estimate landscape-scale reductions in sediment delivery to streams from road surface erosion with BMP upgrades in sample watersheds; 2) Compare post-BMP upgrade estimates of sediment delivery with background watershed erosion rates; and 3) Examine patterns in sediment delivery to help inform ongoing road management.

## Study Area

The study area is in the Northern and Middle Rockies Ecoregions of western Montana and northern Idaho (Omernik 1987). The climate is continental-maritime, with annual precipitation on PCTC lands averaging 750 mm (Table 1). Typically, 50–70% of annual precipitation falls as snow. Rainfall erosivity in this area is among the lowest in the nation (Renard et al. 1997). This is due to the small fraction of total annual precipitation in the summer, when higher-intensity convective storms occur. Stream densities in study watersheds based on the National Hydrography Dataset (NHD) average 2.0 km/km$^2$ (Table 1).

Most of the study area is underlain by metasedimentary Precambrian rocks of the Belt Supergroup, which is primarily composed of argillites, quartzites, and limestones (Ross 1963). In northwestern Montana, approximately 75% of the landscape is covered by tills that were deposited following retreat of Quaternary continental and alpine glaciers (Johns 1970). Tills are primarily derived from Belt Supergroup parent materials. The Hydrologic Soil Group classifications for study area soils are dominated by Groups A and B (USDA 2007). These groups have low-to-moderate runoff potential, with saturated hydraulic conductivities greater than 3.6 cm/hr. Roadbed soil textures for both tills and residual soils formed in the

### Management and Policy Implications

Many forest roads were constructed prior to state adoption of forestry BMP programs, and these legacy roads can contribute significant quantities of sediment to streams. Over time, forest landowners and agencies are upgrading legacy roads to current BMP standards. But no previous estimates of landscape-scale benefits of such BMP implementation exist for this region. Our repeated road inventories and modeling estimates that sediment delivery from road surface erosion was reduced by 46% during a 10–15-year period of systematic BMP upgrades. This research also highlights the importance of field inventories, which can identify the minority of crossings that contribute the majority of sediment to streams. While there are other mechanisms for road sediment to enter streams, such as landslides and stream crossing failures, our results suggest that road surface erosion with BMP implementation can be managed to contribute a small fraction of watershed sediment loading rates in this region.

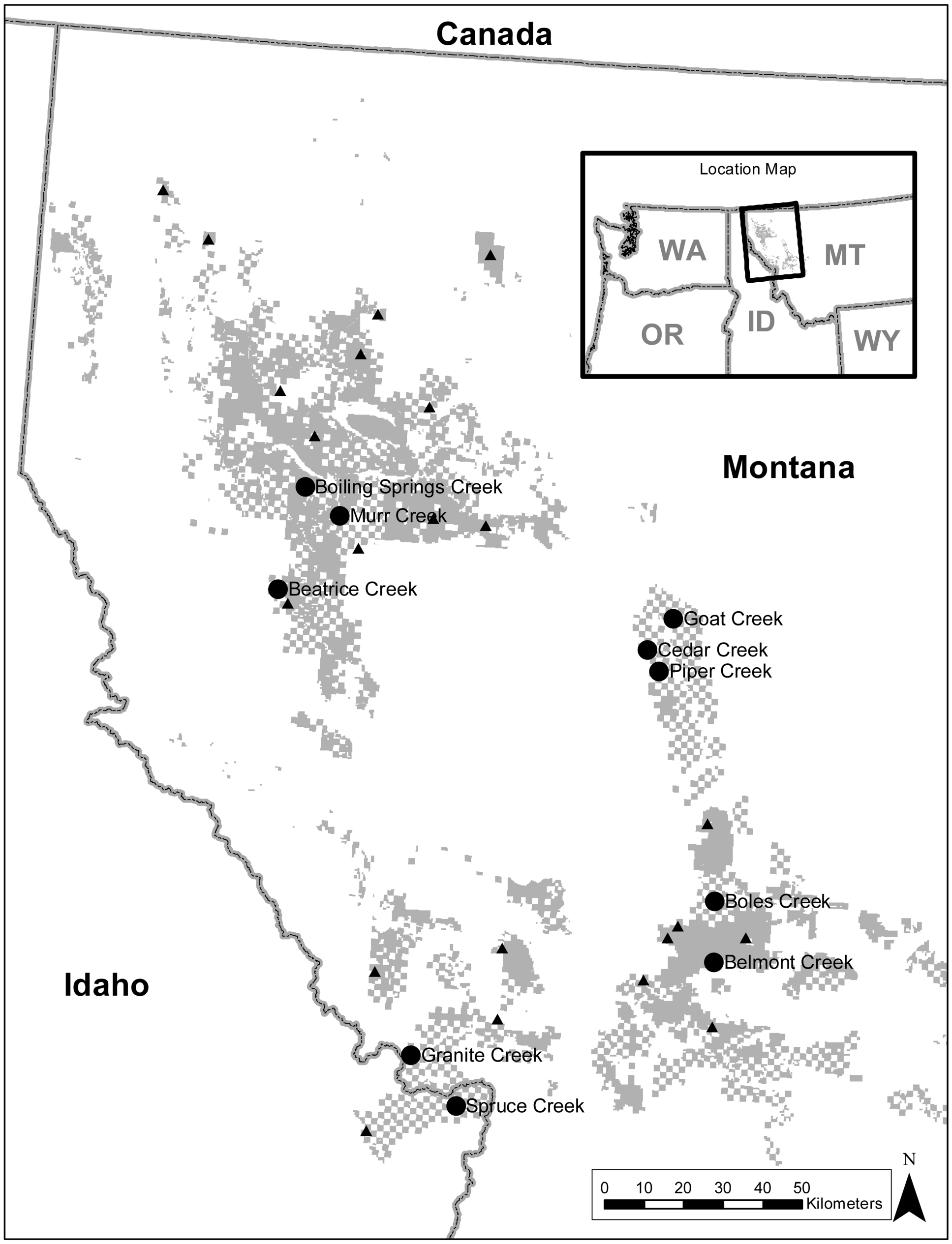


**Figure 1. Locations of ten repeated-inventory road sediment delivery study watersheds (circles), and 22 post-BMP upgrade study watersheds (triangles). Plum Creek Timber Company (PCTC) ownership (as of 2000) is in gray shade.**

Belt Supergroup tend to be very or extremely gravelly sandy or silt loams (Packer 1967, Sugden and Woods 2007). The distribution of soil types on PCTC land in the study area is: glacial till (45%), residual soils in Belt Supergroup (34%), granitic (2%), and other types (e.g., alluvial, lacustrine, and volcanic) based on mapping compiled by Ford et al. (1997).

Road grades in the study area average 6.9% (Standard Deviation 3.7%) in Belt geology and 5.1% (Standard Deviation 3.0%) in tills (Parker 2005). With this precipitation regime and rocky soils, most study area roads are un-ditched and the running surface outsloped, with additional drainage provided by drivable drain dips (also commonly referred to as broad-based, rolling, or grade dips). These dips are excavated into the road running surface and convey water off the road and onto the hillslope below. They are permanent structures, and can be negotiated by log trucks. Drivable drain dips have more diffuse lead-outs than ditch relief culverts, and less concentrated flow, so sediment travel distances are substantially shorter than below relief culverts (Megahan and Ketcheson 1996, Woods et al. 2006). Because of the predominance of gravelly glacial till and residual soils, most roads in this area are native-surfaced. However, this type of surfacing requires attention to wet weather haul conditions and frequent road surface drainage (Packer 1967). Ditched roads are estimated to comprise about 20% of study area roads, with the road running surface generally constructed with a crown.

## Methods

Road sediment delivery to streams was estimated using the Washington Road Surface Erosion Model (WARSEM) (WFPB

**Table 1. Attributes of 10 repeated-inventory watersheds, 22 post-BMP upgrade watersheds, and the entire PCTC ownership in the study area.**

| Watershed name | Assessment year(s) | Geologic type(s) | Watershed area | Mean annual precipitation | Total road length | Watershed stream density | Number of inventoried delivery locations following upgrades | Road hydrologic connect-ivity before and (after) upgrades |
|---|---|---|---|---|---|---|---|---|
| *Replicated inventory watersheds* | | | *km² (%PCTC)* | *mm* | *km (%PCTC)* | *km/km²* | *Count* | *%* |
| Beatrice | 1997, 2005, 2010 | Belt, Till | 26.6 (47%) | 984 | 97.6 (65%) | 2.5 | 38 | 8.2 (5.9) |
| Belmont | 1994, 2005, 2010 | Belt | 77.2 (83%) | 734 | 324.1 (85%) | 2.3 | 109 | 15.4 (6.0) |
| Boiling Springs | 1997, 2005, 2010 | Till | 22.2 (85%) | 736 | 85.2 (91%) | 1.9 | 24 | 2.5 (1.6) |
| Boles | 1998, 2005, 2010 | Till, Belt | 53.6 (37%) | 904 | 128.9 (76%) | 1.9 | 27 | 1.6 (1.8) |
| Cedar | 1997, 2005 | Till | 77.5 (29%) | 1021 | 91.6 (78%) | 1.9 | 14 | 3.5 (2.0) |
| Goat | 1996, 2005, 2010 | Till | 91.0 (25%) | 1188 | 147.0 (74%) | 2.3 | 20 | 1.4 (1.2) |
| Granite | 1998, 2005 | Granite | 53.8 (33%) | 1155 | 139.1 (62%) | 2.3 | 81 | 8.6 (8.3) |
| Murr | 1997, 2005, 2010 | Belt | 80.6 (49%) | 867 | 208.8 (90%) | 1.4 | 53 | 1.8 (1.3) |
| Piper | 1996, 2005 | Till | 32.1 (21%) | 1096 | 36.8 (82%) | 1.9 | 11 | 2.7 (1.6) |
| Spruce | 1996, 2005 | Belt, Other | 65.1 (37%) | 1178 | 69.3 (95%) | 0.8 | 89 | 17.8 (11.2) |
| Totals | | | 580 (43%) | 986 (Mean) | 1328 (80%) | 1.9 (Mean) | 466 | 6.4% (4.1%) Mean 3.1% (1.9%) Median |
| *Un-replicated post-BMP upgrade watersheds* | | | | | | | | |
| Albert | 2007 | Belt | 36.9 (42%) | 835 | 79.9 (71%) | 2.5 | 11 | (1.5) |
| Ashby | 2006 | Belt, Other | 49.7 (62%) | 534 | 154.6 (89%) | 2.5 | 51 | (2.0) |
| Barnum | 2006 | Till, Belt | 29.7 (78%) | 874 | 73.5 (95%) | 1.7 | 29 | (2.1) |
| Bear | 2005 | Belt | 28.5 (21%) | 898 | 49.2 (66%) | 1.9 | 8 | (7.5) |
| Bear 2 | 2007 | Belt | 12.2 (75%) | 983 | 58.1 (97%) | 2.4 | 27 | (3.3) |
| Big Rock | 2008 | Belt, Till | 85.4 (31%) | 942 | 154.8 (84%) | 2.2 | 70 | (3.2) |
| Blanchard | 2005 | Belt, Till | 71.5 (88%) | 676 | 260.5 (91%) | 2.2 | 59 | (4.0) |
| Blue | 2009 | Till, Belt | 24.7 (85%) | 970 | 73.9 (69%) | 2.0 | 39 | (3.1) |
| Brush | 2003 | Till, Belt | 24.5 (39%) | 782 | 51.8 (68%) | 1.9 | 49 | (8.9) |
| Cow | 2003 | Till, Belt | 42.5 (29%) | 835 | 94.0 (60%) | 1.9 | 28 | (4.8) |
| Fish | 2007 | Till, Belt | 7.2 (34%) | 808 | 24.2 (68%) | 0.9 | 9 | (3.6) |
| Freeland | 2004 | Till, Belt | 32.1 (74%) | 788 | 130.6 (89%) | 2.3 | 41 | (1.8) |
| Johnson | 2004 | Belt, Till | 22.6 (37%) | 797 | 31.9 (94%) | 1.9 | 18 | (6.8) |
| Jungle | 2002 | Till, Belt | 22.2 (68%) | 927 | 105.4 (82%) | 2.1 | 25 | (1.0) |
| Lazy-Swift | 2010 | Till, Other | 62.0 (100%) | 698 | 180.7 (100%) | 1.2 | 24 | (0.6) |
| Little Meadow | 2009 | Till, Belt | 69.0 (93%) | 680 | 267.9 (87%) | 2.2 | 32 | (1.2) |
| Little Wolf | 2006 | Till, Other | 98.8 (70%) | 683 | 276.9 (83%) | 1.9 | 72 | (2.1) |
| Parachute | 2002 | Belt, Other | 10.5 (51%) | 1152 | 49.0 (84%) | 1.9 | 15 | (1.5) |
| Upper Gold | 2009 | Till, Belt | 74.8 (55%) | 912 | 185.0 (94%) | 2.0 | 46 | (2.0) |
| Upper Pipe | 2010 | Till, Belt | 24.2 (49%) | 1013 | 83.4 (66%) | 1.9 | 19 | (1.2) |
| WF Clearwater | 2008 | Till | 87.3 (57%) | 1072 | 267.2 (94%) | 1.7 | 133 | (2.9) |
| WF Gold | 2006 | Till, Belt | 52.0 (59%) | 865 | 125.3 (95%) | 2.0 | 53 | (2.2) |
| Totals | | | 968 (62%) | 858 (Mean) | 2778 (86%) | 2.0 (Mean) | 858 | 3.0% (Mean) 2.1% (Median) |
| Entire PCTC ownership in study area (year 2000) | | Till (45%) Belt (34%) Granitic (2%) Other (19%) | 6073 | 750 | 28,000 | 1.6 | | |

1993). The method relies on field observations of stream crossings and stream-adjacent/parallel road segments to populate a simple empirical model, which estimates long-term average amounts of sediment for roads with similar conditions (Dubé et al. 2004). Roads are carefully inspected, and at each delivery location, the road area that contributes sediment to streams is measured. This area (length and width) is measured separately for each road prism component: cutslope, fillslope, and tread (WFPB 1993). A base erosion rate per unit area of contributing road is assigned based on the local geologic type. WARSEM provides default literature base erosion rates where local data are not available. The base rate is then modified for the traffic level on the road, presence and depth of gravel surfacing, vegetative cover, and precipitation. Modifications to the base erosion rate are derived from literature values contained in WARSEM or other available documented sources. Additional supporting documentation on the methodology is provided by Dubé et al. (2004).

While widely applied across the Pacific Northwest, WARSEM performance at a watershed scale has had limited direct validation. Surfleet et al. (2011) evaluated WARSEM in an Oregon and California watershed, and found that predictions were substantially improved with local field measurements of runoff and sediment. With field calibration, WARSEM predictions were within 50% of measured yields. Dubé et al. (2011) also found that field calibration is essential for empirical road erosion models like WARSEM if absolute values are needed.

For this study, base erosion rates were obtained from erosion plot data for PCTC roads in the study area in Belt Supergroup and glacial till soils (Sugden and Woods 2007). In each soil type, 10 road plots were selected based on a stratified random sampling of the PCTC road network. Each plot was measured for three years, and a regression model was fit to the data. The model explained 68% of the variability in sediment yield. Based on the regression model, a WARSEM base erosion rate for each soil type was calculated for a 7% roadbed slope that is annually maintained by road grading. Base erosion rates were 1.0 Mg/ha/yr for roads in Belt Supergroup soils, and 4.3 Mg/ha/yr in glacial till soils (Sugden and Woods 2007).

A second key model assumption in WARSEM is the fraction of total erosion from the inventoried contributing area that delivers to streams (i.e., the delivery ratio or percentage). In cases of direct sediment delivery to streams via a gully or ditch, 100% delivery was assumed per the standard methodology (WFPB 1993). Other drainage features within 60 m of streams were evaluated for indirect (overland) delivery. To do this, the surveyor walked downslope of drainage feature outfalls, following visible sediment flow paths to their end. Observations were made on slope steepness, sediment deposits, hillslope obstructions such as down logs and vegetation, distance from the sediment flow path terminus to the stream, and any designed mitigations in place (such as slash filter windrows). Based on these observations, the surveyor assigned an indirect delivery percentage ranging from zero (no delivery) to 100%. If a visible sediment flowpath ended more than 10 m from the stream, zero delivery was assigned. Sediment flowpaths terminating closer to the stream than 10 m were generally assigned 10 to 50% delivery, based on field observations of the sediment plume and travel distance, and guided by sediment plume volume versus distance relationships for granitic soils developed by Megahan and Ketcheson (1996). Overland sediment flowpaths reaching the stream were generally assigned a delivery rate of 75–100%. Unless the stream was located very close to the erosion source, this delivery ratio is conservatively high (Megahan and Ketcheson 1996, Ward and Jackson 2004, Lakel et al. 2010). Subsequent to the majority of these road inventories being completed, sediment travel distance below drivable drain dips in the study area was evaluated for glacial till and Belt Supergroup soils (Parker 2005, Woods et al. 2006). They found mean travel distances (as measured from the toe of fillslopes) of 4.0 m for tills and 3.2 m for Belt Supergroup geology. Dimensionless curves of sediment plume volume versus distance from source in tills and Belts were similar to those developed by Megahan and Ketcheson, though slightly more linear. This is likely explained by the finer soil textures in the study area.

Between 1994 and 1998, PCTC did a road inventory and estimated road sediment delivery with WARSEM for 10 watersheds in the study area prior to most BMP upgrades being undertaken (shown as circles in Figure 1). Six study watersheds in the Swan and Thompson River Basins were selected to represent variation within these basins and across the company's larger western Montana ownership. The other four study watersheds were selected because of perceived sediment delivery impacts, or to support environmental assessments for federal land access. These 10 baseline assessments from the 1990s were repeated in 2005 and 2010 as BMP upgrades were in progress to estimate reductions achieved by road upgrading (Table 1). Re-measurements were made on this schedule unless the land was sold, or the company did no BMP upgrades or new watercourse crossings.

An additional 22 watersheds were inventoried and modeled using WARSEM over the time period 2002–2010 after BMP upgrades had been completed (Table 1, Figure 1). The assessments were completed in watersheds with populations of native trout, highly erodible soils, or in areas that supported state water-quality planning. These additional assessments serve as an expanded sample to compare road sediment delivery estimates to the 10 repeated-inventory watersheds. Combined, the 10 repeated-inventory watersheds and the 22 additional watersheds encompass 14% of PCTC ownership in the study area (Table1).

The WARSEM methodology allows for sampling of the road network. However, in nine of the 10 repeated watersheds in this study (and all 22 post-BMP watersheds), all stream crossings and stream-adjacent roads were assessed. The one exception is Belmont Creek, where the road network was stratified and sampled in the baseline data collection year of 1994. In Belmont, the strata of moderate-traffic roads was 100% sampled, and strata of light-use roads was 10% sampled. In aggregate, 25% of the road network was sampled in the baseline year. In reassessments of Belmont Creek, a 100% inventory was conducted.

Only road sediment delivery points that were connected to downstream waters were included in the sediment budget for watersheds. For example, sediment delivery to an intermittent stream was not included in the watershed sediment budget if the channel entirely disappeared downslope and no sediment routing to downstream waters was deemed possible. This lack of stream connection is not uncommon in the semi-arid, post-glaciated landscape of western Montana.

Quality assurance and control of field data was managed in several ways. In addition to the author, three hydrologists with forest road BMP experience performed all surveys. If a hydrologist had no prior training in the WARSEM field data collection protocol, field training was provided by the author, who is trained in the methodology by WFPB. Unless the author was also present, hydrologists worked individually to inventory watersheds. All assessments were reviewed and field-checked. For consistency, repeated watershed surveys were performed by the same hydrologist, and the prior inventory data was reviewed to see what specific conditions had changed at each delivery location.

Throughout the entire study area, the BMP condition of all roads, based on PCTC forester field inspections, was tracked in a geographic information system (GIS). The GIS road information was updated annually, based on additional inspections and road upgrading that was accomplished. This landscape-scale tracking provided a basis for evaluating confidence in extrapolating results from sample watersheds to the larger study area.

Background sediment yields for watersheds in or near the study area were obtained from all available sources that could be located, both in the published literature and other available federal agency monitoring data. This search was restricted to less disturbed forested watersheds draining less than 100 km$^2$ to be most comparable to our study watersheds.

## Results

Across PCTC ownership in this landscape, 44% of the road network in 1998 was compliant with BMPs (Figure 2). Between 1998 and 2005, approximately 6% of company roads were upgraded annually, after which time the pace slowed to about 1% annually, until the NFHCP BMP upgrade commitment was fulfilled at the close of 2015. During the period 2001–2015, 330 km of PCTC

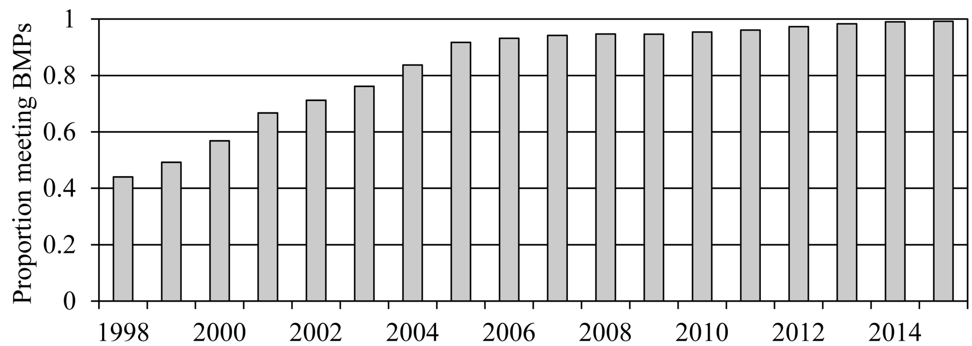


**Figure 2. The proportion of Plum Creek Timber Company (PCTC) roads in the western Montana and northern Idaho study area meeting road best management practices (BMPs) by year, based on PCTC forester inventories as tracked in GIS.**

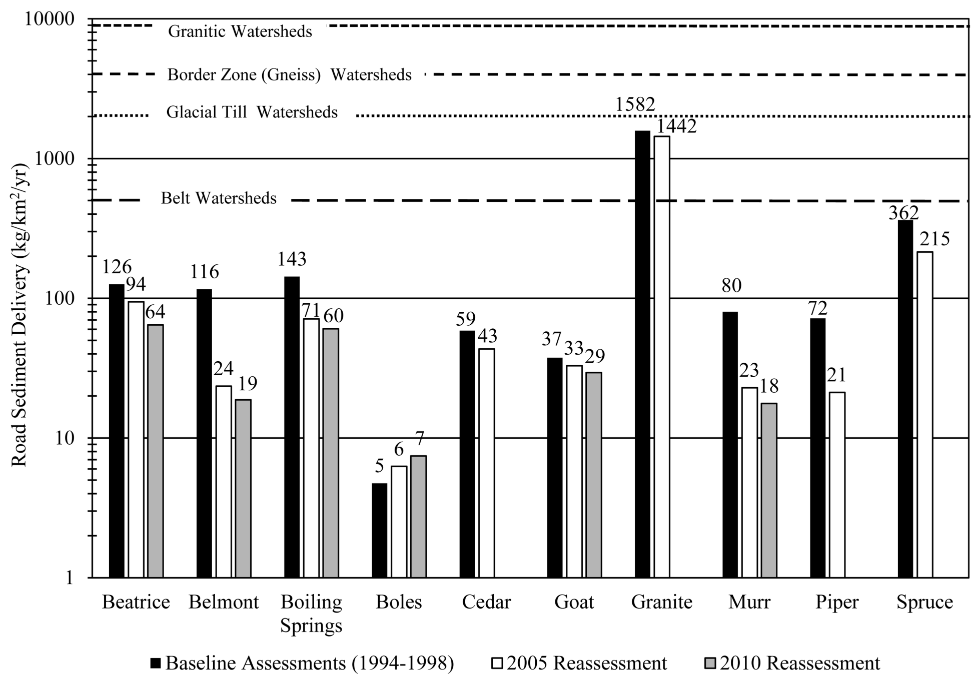


**Figure 3. Estimated sediment delivery to streams from surface erosion (kg/km²/yr) for 10 repeated-inventory study watersheds in western Montana and Northern Idaho by survey year. Horizontal bands are lower-range estimates of background watershed sediment loading from less disturbed forest watersheds draining less than 100 km².**

roads were decommissioned across the study area, and 940 km were constructed.

Weighted by length of PCTC roads, the mean estimated reduction in sediment delivery from road surface erosion in the 10 repeated-inventory watersheds was –46% (Figure 3). The observed range was –84% (Belmont Creek) to +57% (Boles Creek). Median road sediment delivery per unit watershed area was 36 kg/km²/yr. A higher mean rate of 192 kg/km²/yr (Standard Deviation = 443 kg/km²/yr, Standard Error = 140 kg/km²/yr) was driven by the high erosion rate in Granite Creek, which is in the southwestern corner of the study area and in the 2% of the study area containing granitic soils. Nine of 10 watersheds had reduced delivery compared to the baseline. Explanation of watershed-specific results is provided in the Discussion section.

For 22 post-BMP watersheds inventoried between 2002 and 2010, the median watershed sediment delivery was 48 kg/km²/yr, and the mean was 54 kg/km²/yr (Standard Deviation = 37 kg/km²/yr, Standard Error = 8 kg/km²/yr). A box plot comparing the BMP upgraded condition in the 10 repeated-inventory watersheds with the 22 post-BMP watersheds suggests similar estimated delivery rates (Figure 4).

In the 10 repeated watershed baseline inventories, 6.4% (Range: 1.4–17.8%) of the total road length was found to contribute directly or indirectly to streams (i.e., was "hydrologically connected"). After upgrading, the mean connectivity decreased to 4.1% (Range: 1.2–11.2%) (Table 1). For the 22 post-BMP watersheds, the mean connectivity was 3.0% (Range: 0.6–8.9%).

A majority of estimated sediment delivery occurred at a minority of road stream crossings inventoried. From the baseline inventories in the 10 watersheds (2005 inventory for Belmont), 25% of inventoried crossings contributed 50–75% of total watershed sediment delivery (Figure 5).

# Discussion

## Watershed-Specific Results

Watershed-specific reduction in road sediment delivery was variable (Figure 3). The greatest estimated reduction in sediment

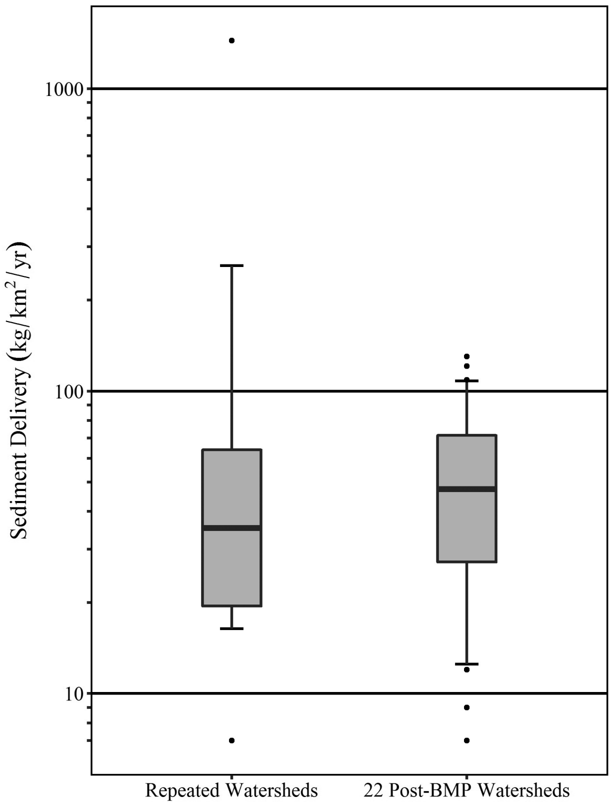


**Figure 4. Estimated annual sediment delivery to streams in 10 repeated-inventory watersheds (post-upgrades) and in 22 other post-BMP upgrade watersheds inventoried between 2002 and 2010. Solid horizontal line in middle of box indicates the median. Box ends indicate the 25th and 75th percentiles. Whiskers indicate the 10th and 90th percentiles. Outliers shown as black dots.**

delivery was in Belmont Creek (–84%). This watershed had the oldest baseline inventory (1994), and few road segments met BMPs at that time (Sugden 1994). Additionally, PCTC managed almost all of the road network in the Belmont Creek watershed, providing the most opportunity for BMP upgrades to positively affect delivery rates.

Boles Creek was the only watershed to experience an increase in estimated sediment delivery, but it had the lowest absolute loading rate of the 10 repeated-inventory watersheds, at 7 kg/km$^2$/yr (Figure 3). In the baseline year of 1998, road BMPs were generally applied across the Boles Creek watershed, limiting the sediment reduction benefit of additional upgrades. For the 18 original crossings inventoried in Boles in 1998, sediment delivery was reduced 18% by 2010. However, 13 km of new road was built in this basin with current BMPs (after the baseline inventory), which added seven new sediment delivery locations (five crossings and two stream-adjacent segments). Despite being constructed with current BMPs, these new roads and their active use increased total sediment delivery at a watershed level.

Granite Creek had the highest estimated delivery at 1442 kg/km$^2$/yr. Roads in this watershed are constructed in granitic soils, which are substantially more erodible than the other soils in the study area. For this inventory, we relied on the WARSEM default base erosion rate for established roads in granitic soils (67 Mg/ha/yr), which was based on research conducted in the Idaho Batholith of central Idaho (WFPB 1993). It could be that actual base erosion rates in Granite Creek differ from the Idaho Batholith research, but we had no location-specific data to support modification of the WARSEM rates such as we had for glacial tills and Belt Supergroup materials. Granite Creek had only a 9% decrease in estimated delivery reduction. The primary reason for this relatively small reduction is that many higher-delivery locations were on roads for which PCTC did not have management responsibility.

Spruce Creek in Idaho had a near-average reduction in estimated delivery (–41%), but the post-upgrading absolute rate was second highest, at 215 kg/km$^2$/yr. Spruce Creek has one of the highest precipitation rates of study watersheds at 1178 mm/yr. While the calculated stream density based on NHD is only 0.9 km/km$^2$ (Table 1), the on-the-ground stream density is much higher in this watershed. Because of this, the number of delivery locations per unit road length is the highest of any study watershed.

### BMP Evaluation

Exploration of the 10-watershed dataset found that most of the decrease in estimated sediment delivery was explained by reducing the length of road delivering to streams, which decreased by 36%. This was typically done by installing drivable drain dips in the road surface so that runoff distances generally did not exceed 75 to 125 m. Near streams, drivable drain dips were located as close to the stream crossing as possible while still ensuring effective filtration below the dip outlet. The remaining reduction in sediment delivery was achieved through other BMPs. One included improved management of public use through seasonal or annual road use restriction via gates or barricades. Road use restriction reduced the frequency of road grading and increased vegetative cover on roads, the combined effect being substantially lower road erosion rates (Luce and Black 2001, Sugden and Woods 2007, Al-Chokhachy et al. 2016). Improvements to filtration near stream crossings, both on the fill above road culverts, and below drainage feature outfalls near streams, also contributed to reduction in road sediment delivery. Filtration improvements included widespread use of grass seeding, straw mulch, and slash filter windrows, which have all been shown to be highly effective at reducing erosion and sediment delivery (Cook and King 1983, Burroughs and King 1989, NCASI 2009, Wade et al. 2012). Twelve kilometers of road was decommissioned during the study in the replicated watersheds, but this had little overall effect on watershed sediment loading rates since these roads were not in priority delivery areas.

### Hydrologic Connectivity

Watersheds with higher hydrologic connectivity (Table 1) tended to have more stream-adjacent roads where delivery could not be fully mitigated, more roads for which PCTC had no management control, or areas with greater annual precipitation and higher associated stream density (i.e., Spruce, Granite, and Brush Creeks). Watersheds with lower hydrologic connectivity were often in glaciated terrain where the majority of roads were in areas with low stream densities and fewer crossings (e.g., Goat Creek, Lazy-Swift Creek). Hydrologic connectivity cannot reach zero, as there will always be some remaining road segment that cannot be fully disconnected at stream crossings. However, additional BMPs can be employed to reduce the fraction of road surface erosion being delivered to streams at these locations. Examples of these BMPs include slash filter windrows, silt fences, and infiltration basins.

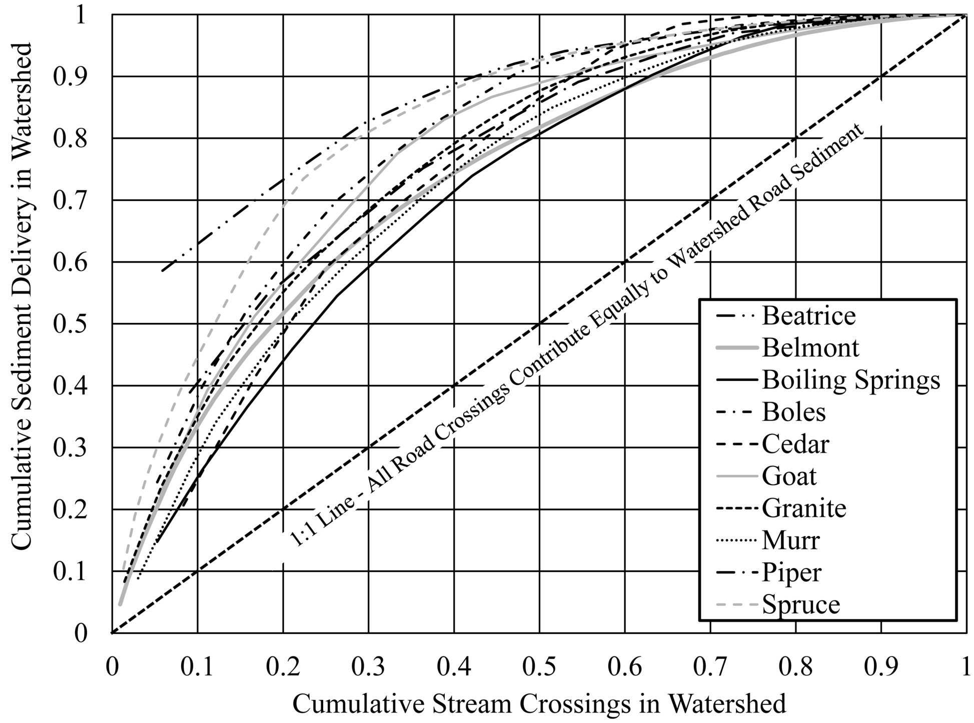


**Figure 5. Cumulative sediment delivery from stream crossings in each study watershed as a function of cumulative stream crossings.**

Another investigation of road hydrologic connectivity in the study area was completed by the US Forest Service in 2012–2013, and two of their study watersheds included significant land recently acquired from PCTC (Cissel et al. 2014, Al-Chokhachy et al. 2016). They reported mean road hydrologic connectivity in these areas of 4%, which is consistent with these results.

In Washington, legacy forest roads are being addressed through Road Maintenance and Abandonment Plans (RMAP). In eastern Washington, which has precipitation patterns and stream densities similar to this study area, Dubé et al. (2010) reported 6% mean (4% median) hydrologic connectivity for roads after most RMAP BMP upgrades had been completed. This level of hydrologic connectivity is similar to our study, and substantially lower than the wetter climate and higher associated stream densities in western Washington (Bilby et al. 1989, Dubé et al. 2010).

#### Patterns in Estimated Delivery

The finding that a small percentage of road crossings both generate and deliver the majority of sediment to streams (Figure 5) has important implications for managing stream sediment loading across managed forest landscapes. A simple analysis of watershed road density or a GIS intersection of roads with streams may identify places to prioritize field investigation, but erosion and delivery can only be assessed by on-the-ground inspection. Knowledge of site-specific conditions is essential to determining locations where BMP upgrades would achieve the highest impact for the lowest cost. Such conditions include the presence of direct-delivery ditches or road surface runoff, road ruts, actively eroding road cutslopes, vegetative cover, presence of gravel surfacing, and sediment filtration BMPs such as slash filter windrows. This observation has been reported by others who have conducted similar road inventories (McGreer et al. 1998, Al-Chokhachy et al. 2016).

Interestingly, even after upgrading, it was found that the dimensionless cumulative delivery curves shown in Figure 5 retained a non-linear shape. While watershed sediment delivery may sharply decline following BMP upgrades, there are still locations that inherently contribute more sediment at a watershed scale. This is the result of most watersheds having a mix of more and less heavily trafficked roads, difficult situations to fully mitigate, and many well-vegetated roads that contribute very little to watershed sediment delivery.

#### Background Erosion Rates

While a 46% decrease in road sediment delivery is substantial, it is helpful to place loading rates into context with total watershed suspended sediment yields. Background yields in the northern Rockies have been found to vary by orders of magnitude based on the time scale examined, with shorter (more recent) periods usually having substantially lower measured yields than longer periods due to the disproportionately large effect of infrequent events such as floods following wildfire (Kirchner et al. 2001). A range of published and unpublished estimates of sediment yields from small forest watersheds in this region by geologic type indicates that estimates of background sediment loading for these watersheds have levels of confidence that range from low (suspended sediment grab samples) to moderate/high (research watershed data—installed flumes, automated sampling). Data found for the study region are summarized in Table 2.

Based on the studies in Table 2, the range in yields for different geologic materials are: Belt Supergroup (500–2000 kg/km$^2$/yr); glacial tills (2000–6000 kg/km$^2$/yr); northern Idaho gneiss/Belt Supergroup (4000–7000 kg/km$^2$/yr); and Idaho Batholith granitics (~9000 kg/km$^2$/yr). Using the lower range from the range of background erosion rates for the different geologic groupings (horizontal lines in Figure 3) indicates that the sediment contribution by

Table 2. Annual background watershed sediment yields in various geologies from the region of this study. Yields footnoted with an asterisk include some bedload fraction.

| Location | Predominant surficial geology | Length of record | Total suspended sediment yield | Data source | Level of confidence |
|---|---|---|---|---|---|
| | | *years* | *kg/km²/yr* | | |
| Johnson Gulch, MT | Belts | 5 | 500 | Anderson and Potts (1987) and subsequent unpublished data | Moderate/High |
| NF Blackfoot River, MT | Belts, Till | 18 | 2800 | Lolo National Forest unpublished data (from Cissel et al. 2014) | Low |
| Lion Creek, MT | Till, Belt | 9 | 2800 | Flathead NF Forest Plan monitoring data, unpublished | Low |
| Elk Creek, MT | Till, Belt | 9 | 6000 | Flathead NF Forest Plan monitoring data, unpublished | Low |
| Goat Creek, MT | Till, Belt | 7 | 2200 | Flathead NF Forest Plan monitoring data, unpublished | Low |
| Mica Creek, ID Watershed 1 | Gneiss / Quartzite | 6 | 5500 | Karwan et al. 2007 | Moderate/High |
| Mica Creek, ID Watershed 2 | Gneiss / Quartzite | 6 | 6000 | Karwan et al. 2007 | Moderate/High |
| Mica Creek, ID Watershed 3 | Gneiss / Quartzite | 6 | 4400 | Karwan et al. 2007 | Moderate/High |
| Horse Creek, ID East Fork | Gneiss / Belts | 13 | 4500* | Larson and Sidle 1980 | Moderate/High |
| Horse Creek, ID West Fork | Gneiss / Belts | 13 | 7500* | Larson and Sidle 1980 | Moderate/High |
| Silver Creek, ID WS-3 (Control) | Granitic | 28 | 8900* | Kirchner et al. 2001 | Moderate/High |

roads after BMP upgrades in this area typically fall between 1 and 5% of background watershed sediment yield. Beatrice Creek roads were higher, at 13% of the lower-range background estimate and 3% of higher-end range, due to a higher fraction of stream-adjacent road contribution that could not be fully mitigated without road removal. Roads in Granite Creek are estimated to deliver about 16% of background sediment yield, but additional BMP upgrade opportunities still exist in that watershed. While background erosion estimates based on suspended sediment measurement can be subject to significant errors (Bunte and MacDonald 1999), this comparison does suggest that roads in this region, if managed properly, can contribute a relatively small fraction of total watershed sediment yields.

### Applicability of Results

These findings compare favorably with those of Cissel et al. (2014), who evaluated former PCTC land in the study area. They used the Geomorphic Road Assessment Inventory Procedure (GRAIP) model (Black et al. 2012), which is also based on field-obtained data. For their three study areas, Cissel et al. reported road surface erosion contributions of 100, 190, and 210 kg/km²/yr. These values are slightly higher than rates we observed at most of the repeated-inventory and post-BMP watersheds in this study (Figure 5). Cissel et al. estimated that their road sediment delivery rates represented 1–2% of background rates.

Estimated road sediment delivery per unit watershed area is very low in this western Montana and northern Idaho study area. Factors that contribute to this include: 1) low amounts of summer rainfall and thus low annual rainfall erosivity; 2) a relatively low stream drainage density; 3) the low erodibility of coarse soils (Packer 1967, Sugden and Woods 2007); and 4) some streams are discontinuous, lacking a surface flow connection to downstream waters.

PCTC only had direct, or shared, management responsibility for about 85% of the roads in these watersheds (Table 1). The pace of BMP upgrades on roads managed by other owners was slower than that on PCTC lands, so full upgrading of all roads did not occur in many of these watersheds. If baseline data for all study watersheds been collected in the late 1980s prior to any road upgrades, it is likely that the documented reductions would have been even greater. It is possible that moving from a no-BMP road network to a full-BMP road network could have reduced loading on the order of 80–90%, which is consistent with results for Belmont Creek, and other estimates of BMP effectiveness (NCASI 2009, Reiter et al. 2009, Ice and Schilling 2012, Nolan et al. 2015, Cristan et al. 2016).

Legacy road BMP upgrading is occurring in Montana across all ownership categories. Between 2000 and 2010, state BMP implementation monitoring revealed that two-thirds of audit sites in Montana had legacy road BMP improvements that were judged by audit teams to have reduced overall sediment loading in the watershed (Sugden et al. 2012). This clearly demonstrates that active management provides opportunities for landowners to make significant improvement to reducing sediment delivery by upgrading legacy roads to modern state BMPs.

## Sources of Uncertainty

The assigned base erosion rates and determination of indirect delivery are the factors with greatest uncertainty in the estimation of sediment delivery to streams using the model we employed. This uncertainty was reduced by the application of locally derived base erosion rates (Sugden and Woods 2007) and local information on downslope sediment movement below drivable drain dips (Parker 2005, Woods et al. 2006). However, there are additional sources of variability that are not accounted for in the regression model developed by Sugden and Woods (2007). Hydrologic measurements of road runoff likely could have helped improve our prediction of onsite road erosion in the WARSEM model (Surfleet et al. 2011). Cissel et al. (2014) conducted an independent analysis of road sediment loading in several watersheds in the study area that included former PCTC lands and roads. They collected their own empirical data on road erosion, used a different model (GRAIP), and reported results comparable to those in this paper (see also Al-Chokhachy et al. 2016).

Study watersheds were not randomly sampled. Rather, they were selected over time to represent the diversity of the soil types and terrain across the study area, and address other management questions. Sites ended up being well distributed across PCTC ownership (Figure 1); and combined, they represent 14% of the total ownership. Tracking condition of all roads in the PCTC GIS shows that BMP upgrades were applied across the landscape, and that results from sample watersheds should be broadly applicable.

Field measurements and determinations of sediment delivery percentages were made by four trained hydrologists, and the same hydrologist conducted repeated inventories. Spot-checks of field inventory data found that data were properly and consistently collected. Most inventories were made during dry-season conditions of late spring and summer (June, July, and August). However, evidence of sediment flowpaths in these silty soils generally remain visible during the dry season. Hydrologists were instructed to be conservative in determinations of indirect delivery percentages, and local data on sediment movement below drivable drips suggests this was the case (Parker 2005, Woods et al. 2006). Nonetheless, this is a source of uncertainty.

This study did not explore other potential road-related watershed sediment sources, such as landslides, gullies, or culvert failure, which may be locally significant (Al-Chokhachy et al. 2016). BMP upgrades over time are increasing the size of culverts, which is undoubtedly reducing failure risk, but is unquantified. Landslide risk in this study area is generally low relative to other parts of the Pacific Northwest (McGreer et al. 1998), but when landslides occur and deliver sediment to streams, it can represent a significant part of the watershed sediment budget.

## Conclusion

This study found that as a large legacy road network on industrial forestland in the northern Rocky Mountains was systematically upgraded to current BMPs over a 10–15-year span, a 46% reduction in surface erosion sediment delivery to streams was estimated by a road surface erosion model. In the Belt Supergroup and glacial till soil types in this study area, road surface erosion where BMPs are fully applied is estimated to contribute less than 5% of background sediment loading rates.

Road surface erosion modeling based on comprehensive field surveys indicates that sediment delivery in these watersheds is dependent on the site-specific BMP conditions, and that a majority of watershed sediment delivery occurs at a minority of crossing locations. Field inspection by BMP-trained personnel can identify and prioritize BMP improvements or maintenance.

The road network assessed had a high level of forest management activity during the study period, which allowed for efficient BMP upgrades. While BMP upgrades were completed by the end of 2015 under a Native Fish Habitat Conservation Plan, most upgrades would have occurred anyway under state BMPs and corporate commitments under the SFI forest management standard. State monitoring of BMP implementation on private and public lands in Montana indicates that legacy road BMP improvements are being made across all ownership categories.

### Endnote

1. In 2016, Plum Creek Timber Company (PCTC) merged with Weyerhaeuser. About half of the original land base described in this study is currently owned by Weyerhaeuser, with most of the remaining acreage now in federal or state ownership.

## Literature Cited


Al-Chokhachy, R., T.A. Black, C. Thomas, C.H. Luce, B. Rieman, R. Cissel, A. Carlson, S. Hendrickson, E.K. Archer, and J.L. Kershner. 2016. Linkages between unpaved forest roads and streambed sediment: Why context matters in directing road restoration. *Restoration Ecol.* 24(5):589–598.

Anderson, B., and D.F. Potts. 1987. Suspended sediment and turbidity following road construction and logging in western Montana. *Water Res. Bull.* 23(4):681–690.

Bilby, R.E., K. Sullivan, and S.H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. *For. Sci.* 35:453–468.

Black, T.A., R. Cissel, and C.H. Luce. 2012. *The Geomorphic Road Analysis and Inventory Package (GRAIP) volume 1: Data collection method*. USDA For. Serv. Gen. Tech. Rep. RMRS-GTR-280WWW. 110 p.

Bunte, K., and L. MacDonald. 1999. *Scale considerations and the detectability of sedimentary cumulative effects. Technical Bulletin No. 776*. National Council for Air and Stream Improvement, Inc. Research Triangle Park, NC. 327 p.

Burroughs, E.R., and J.G. King. 1989. *Reduction of soil erosion on forest roads*. USDA For. Serv. Gen. Tech. Rep. INT-264. 22 p.

Cissel, R., T. Black, N. Nelson, and C. Luce. 2014. *Southwest Crown of the Continent GRAIP roads assessment: Center Horse and Morrell/Trail Project Area, Poorman Creek, and Cold Creek. Lolo, Helena, and Flathead National Forests, Montana*. USDA For. Serv. 113 p. Available online at www.fs.fed.us/GRAIP/downloads/case_studies/WatershedStudies_LoloHelenaFlatheadNFs_SWCC_2014%20Final%20Report.pdf, last accessed January 11, 2018.

Cook, M.J., and J.G. King. 1983. *Construction cost and erosion control effectiveness of filter windrows on fill slopes*. USDA For. Serv. Res. Note INT-135. 6 p.

Cristan, R., W.M. Aust, M.C. Bolding, S.M. Barrett, and J.F. Munsell. 2018. National status of state developed and implemented forestry best management practices for protecting water quality in the United States. *For. Ecol. and Man.* In Press.

Cristan, R., W.M. Aust, M.C. Bolding, S.M. Barrett, J.F. Munsell, and E. Schilling. 2016. Effectiveness of forestry best management practices in the United States: Literature review. *For. Ecol. and Man.* 360:133–151.

Dubé, K., T. Black, C. Luce, and M. Riedel. 2011. *Comparison of road surface erosion models with measured road surface erosion rates. Tech. Bull. No. 988*. National Council for Air and Stream Improvement, Inc. (NCASI). Research Triangle Park, NC. 44 p.

Dubé, K., W. Megahan, and M. McCalmon. 2004. *Washington road surface erosion model (WARSEM)*. Wash. Dept. of Nat. Res., Olympia, WA. 56 p. Available online at http://file.dnr.wa.gov/publications/fp_data_warsem_manual.pdf, last accessed January 11, 2018.

Dubé, K., A. Shelly, J. Black, and K. Kuzis. 2010. *Washington road sub-basin scale effectiveness monitoring first sampling event (2006–2008) report. Cooperative Monitoring, Evaluation and Research Report CMER 08-801*. Wash. Dept. Nat. Res., Olympia, WA. 102 p.

Endicott, D. 2008. *National level assessment of water quality impairments related to forest roads and their prevention by best management practices*. Report prepared for US EPA, Office of Water. Contract No. EP-C-05-066. Great Lakes Environmental Center. 250 p.

Ford, G.L., C.L. Maynard, J.A. Nesser, and D.S. Page-Dumrose. 1997. *Landtype associations of the Northern Region, a first approximation*. USDA For. Serv. 25 p. Available online at https://forest.moscowfsl.wsu.edu/smp/solo/R1LTAs/text/chapt1_2.pdf, last accessed January 11, 2018.

Furniss, M.J., T.D. Roelofs, and C.S. Yee. 1991. Road construction and maintenance. P. 297–324 in *Influences of forest and rangeland management on salmonid fishes and their habitats,* Meehan, W. (ed.). Special Publication 18, American Fisheries Society, Bethesda, Maryland.

Ice, G., L. Dent, J. Robben, P. Cafferata, J. Light, B. Sugden, and T. Cundy. 2004. Programs assessing the implementation and effectiveness of state forest practice rules and BMPs in the west. *Water, Air, and Soil Pollution: Focus* 4:143–169.

Ice, G., and E.B. Schilling. 2012. *Assessing the effectiveness of contemporary forestry best management practices (BMPs): Focus on roads. Special Report 12-01*. National Council for Air and Stream Improvement, Inc., Research Triangle Park, NC. 6 p. Available online at http://www.ncasi.org/Downloads/Download.ashx?id=7589, last accessed January 11, 2018.

Ice, G., G.W. Stuart, J.B. Waide, L.C. Irland, and P.V. Ellefson. 1997. Twenty-five years of the Clean Water Act: How clean are forest practices? *J. For*. 95(7):9–13.

Johns, W.M. 1970. *Geology and mineral deposits of Lincoln and Flathead Counties, Montana. Bulletin 79*. Mont. Bur. of Mines and Geology, Butte, Montana. 182 p.

Karwan, D.L., J.A. Gravelle, and J.A. Hubbart. 2007. Effects of timber harvest on suspended sediment loads in Mica Creek, Idaho. *For. Sci*. 53(2):181–188.

Kirchner, J.W., R.C. Finkel, C.S. Riebe, D.E. Granger, J.L. Clayton, J.G. King, and W.F. Megahan. 2001. Mountain erosion over 10 yr, 10k.y. and 10 m.y. time scales. *Geology* 29(7):591–594.

Lakel, W.A. III, W.M. Aust, M.C. Bolding, C.A. Dolloff, P. Keyser, and R. Feldt. 2010. Sediment trapping by streamside management zones of various widths after forest harvest and site preparation. *For. Sci*. 56(6):541–551.

Larson, K.R., and R.C. Sidle. 1980. *Erosion and sedimentation data catalog of the Pacific Northwest*. USDA For. Serv. Res. Sta. Rep. R6-WM-050-1981. 72 p.

Luce, C., and T. Black. 2001. *Spatial and temporal patterns in erosion from forest roads*. P. 165–178 in *The influence of land use on the hydrologic-geomorphic responses of watersheds*, Wimosta, M.S., and S.J. Burges (eds.). Water Resources Monographs, American Geophysical Union, Washington, DC.

McGreer, D.J., B.D. Sugden, and D.T. Schult. 1998. *Surface erosion and mass wasting assessment and management strategies for Plum Creek's Native Fish Habitat Conservation Plan*. NFHCP Technical Report #3. Plum Creek Timber Company, Columbia Falls, MT. 50 p.

Megahan, W.F., and G.L. Ketcheson. 1996. Predicting downslope travel of granitic sediments from forest roads in Idaho. *Wat. Res. Bull.* 32(2):371–382.

Megahan, W.F., and W.J. Kidd. 1972. *Effect of logging roads on sediment production rates in the Idaho Batholith*. USDA For. Serv. Res. Pap. INT-123. 14 p.

National Council for Air and Stream Improvement, Inc. (NCASI). 2001. *Forest roads and aquatic ecosystems: A review of causes, effects and management practices*. 70 p.

National Council for Air and Stream Improvement, Inc. (NCASI). 2009. *Compendium of forestry best management practices for controlling nonpoint source pollution in North America*. Tech. Bull. No. 966. Research Triangle Park, NC. 230 p. Available online at http://www.ncasi.org/Downloads/Download.ashx?id=10204, last accessed January 11, 2018.

Nolan, L., W.M. Aust, S.M. Barrett, M.C. Bolding, K. Brown, and K. McGuire. 2015. Estimating costs and effectiveness of upgrades in forestry best management practices for stream crossings. *Water* (7):6946–6966.

Omernik, J.A. 1987. Ecoregions of the conterminous United States. *Annals of the Assoc. of Amer. Geogr*. 77:118–125.

Packer, P.E. 1967. Criteria for designing and locating logging roads to control sediment. *For. Sci.* 13(1):2–18.

Parker, B.R. 2005. *Sediment deposition below forest road drivable drain dips in Belt and glacial till parent materials of western Montana*. M.Sc. thesis, Univ. of Montana, Missoula. 53 p.

Reid, L.M., and T. Dunne. 1984. Sediment production from forest roads. *Water Resources Res*. 20(11):1753–1761.

Reiter, M., J.T. Heffner, S. Beech, T. Turner, and R.E. Bilby. 2009. Temporal and spatial turbidity patterns over 30 years in a managed forest of Western Washington. *J. Amer. Wat. Res. Assoc*. 45(3):793–808.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder (eds.). 1997. *Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE).* USDA Agric. Res. Serv. Handbook No. 703. 404 p.

Ross, C.P. 1963. *The Belt Series in Montana*. USDI Geol. Surv. Prof. Pap. 346. Helena, Montana. 119 p.

Sidle, R.C., and H. Ochiai. 2006. *Landslides: processes, prediction, and land use. Water Resources Monograph 18*. American Geophysical Union, Washington D.C. 312 p.

Sugden, B.D. 1994. *Belmont Creek watershed analysis*. Plum Creek Timber Co., Columbia Falls, Montana. 73 p.

Sugden, B.D., R. Ethridge, G. Mathieus, P.E.W. Heffernan, G. Frank, and G. Sanders. 2012. Montana's forestry best management practices program: 20 years of continuous improvement. *J. For.* 110(6):328–336.

Sugden, B.D., and S.W. Woods. 2007. Sediment production from forest roads in western Montana. *J. Amer. Wat. Res. Assoc.* 43(1):193–206.

Surfleet, C., A. Skaugset, and M. Meadows. 2011. Road runoff and sediment sampling for determining road sediment yield at the watershed scale. *Can. J. For. Res.* 41(10):1970–1980.

Sustainable Forestry Initiative (SFI). 2015. *SFI 2015–2019 forest management standard*. 12 p. Available online at http://www.sfiprogram.org/sfi-standard/, last accessed January 11, 2018.

US Department of Agriculture (USDA). 2007. *Hydrologic soils groups. Chapter 7 in National engineering handbook, part 630, Hydrology*. Natural Resource Conservation Service, Washington, DC. Available online at https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17757.wba, last accessed January 11, 2018.

US Environmental Protection Agency (USEPA). 2016. Decision not to regulate forest road discharges under the Clean Water Act; Notice of Decision. *Fed. Reg*. 81(128):43492–43510. Available online at www.gpo.gov/fdsys/pkg/FR-2016-07-05/pdf/2016-15844.pdf, last accessed January 11, 2018.

US Environmental Protection Agency (USEPA). 2017. *Assessment and Total Maximum Daily Load Tracking and Implementation System (ATTAINS)*. Available online at https://ofmpub.epa.gov/waters10/attains_nation_cy.control, last accessed January 11, 2018.

US Fish and Wildlife Service (USFWS), National Marine Fisheries Service, Plum Creek Timber Co., Inc., and CH2M Hill. 2000. *Final environmental impact statement and native fish habitat conservation plan*. 311 p. Available online at www.fws.gov/montanafieldoffice/Endangered_Species/Habitat_Conservation_Plans/Plum_Creek_HCP/Home_pcfeis.htm, last accessed January 11, 2018.

Wade, C.R., M.C. Bolding, W.M. Aust, and W.A. Lakel III. 2012. Comparison of five erosion control techniques for bladed skid trails in Virginia. *South. J. Appl. For.* 36(4):191–197.

Ward, J.M., and C.R. Jackson. 2004. Sediment trapping within forestry streamside management zones: Georgia piedmont, USA. *J. Amer. Wat. Res. Assoc*. 40(6):1421–1431.

Washington Forest Practices Board (WFPB). 1993. *Standard methodology for conducting watershed analysis, Version 2.0*. Wash. Dept. Nat. Res., Resources, Olympia, Washington.

Woods, S.W., B. Sugden, and B. Parker. 2006. Sediment travel distances below drivable drain dips in western Montana. P. 251–263 in *Proc. of conf. on Working globally—sharing forest engineering challenges and technologies around the world*, Chung, W. and H.S. Han (eds.). Council on Forest Engineering, Corvallis, Oregon. Available online at http://www.cofe.frec.vt.edu/documents/2006/COFE_2006_Woods_et_al.pdf, last accessed January 11, 2018.